

Study on the Jointed Rock Mass for the Excavation of Hyper-KAMIOKANDE Cavern at Kamioka Mine

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Topics

- Previous Geological Survey and Stability Analysis for the Hyper-K cavern
 - Site Selection
 - Isotropic Elastic FEM Analysis for the Investigation of Cavern Shape, Size and Type
- Ongoing Investigation and Analysis for Jointed Rock Mass
 - Investigation of Joint Orientation
 - Obtaining In-Situ Rock Joints and Investigation of Joint Mechanical Properties
 - Pull-out Test of Two Types of Cable Bolt
 - Two Type Analysis for Consideration Joint Effects

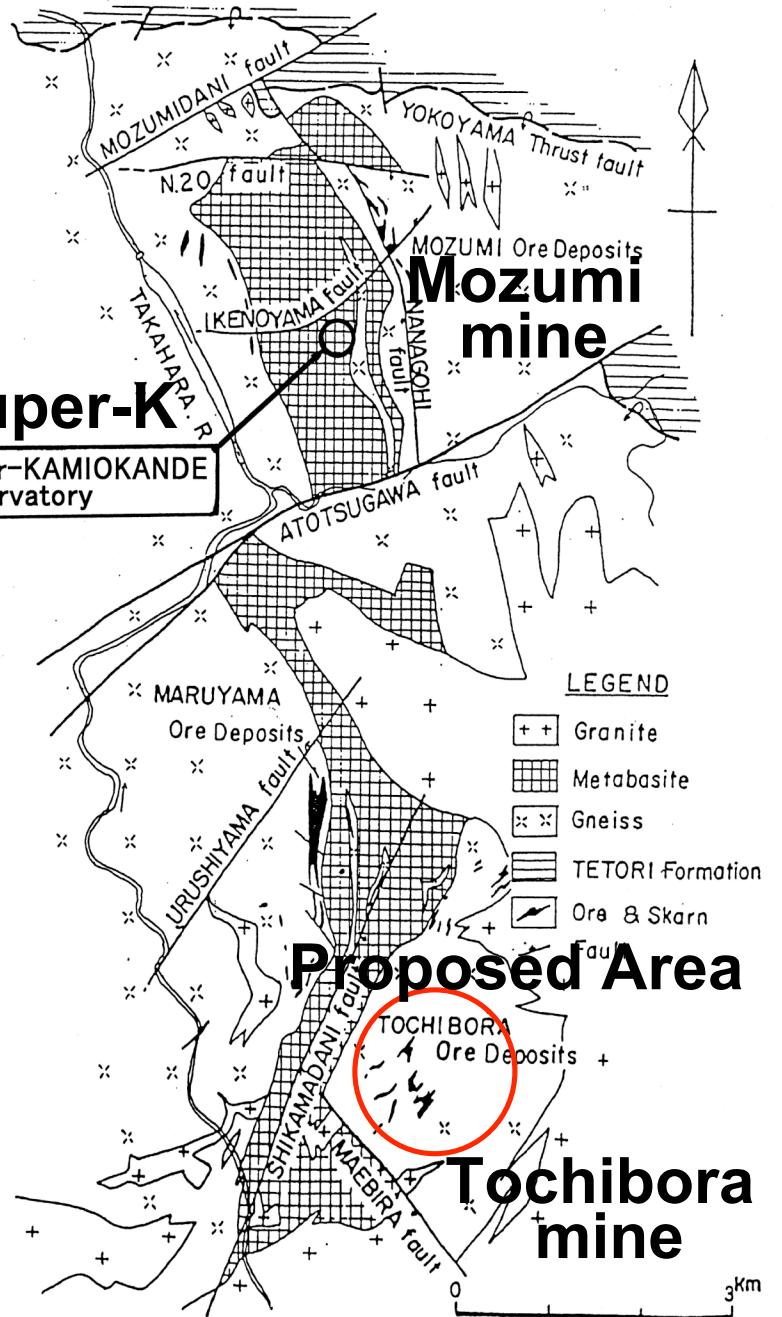
Site Selection

Kamioka Mine Location

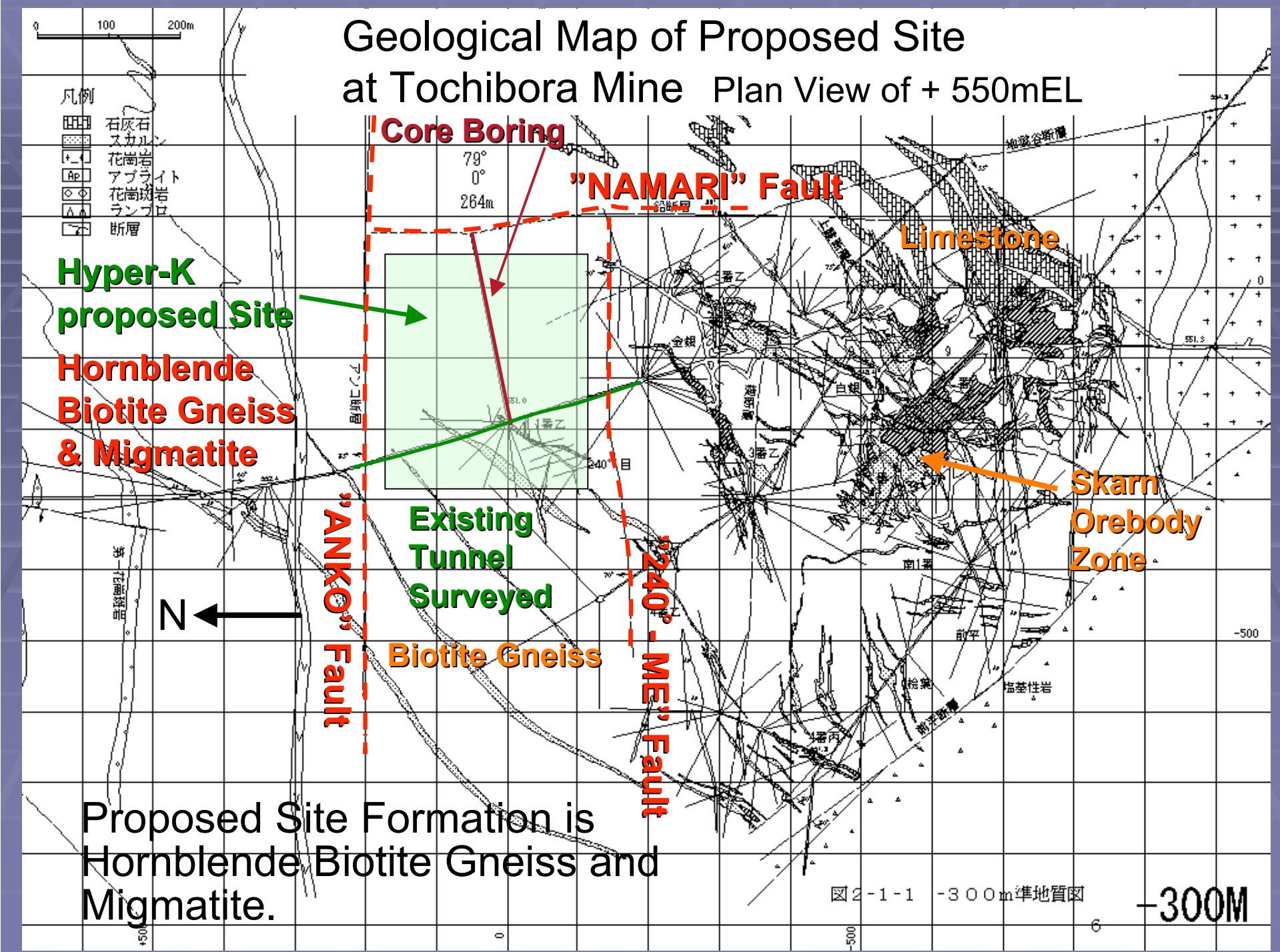


Proposed Area in Mozumi Mine
is about 10km South from the
Super-Kamiokande.

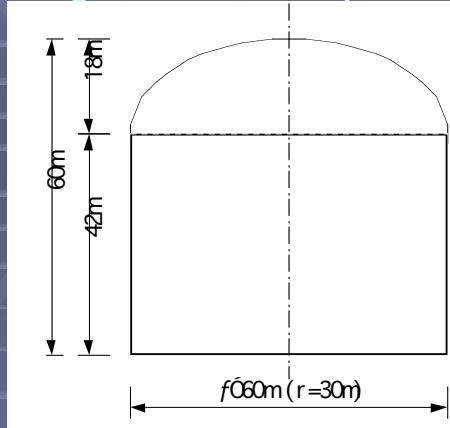
GEOLOGY AND ORE DEPOSITS OF KAMIOKA MINE



Geological Map of Proposed Site at Tochibora Mine Plan View of + 550mEL

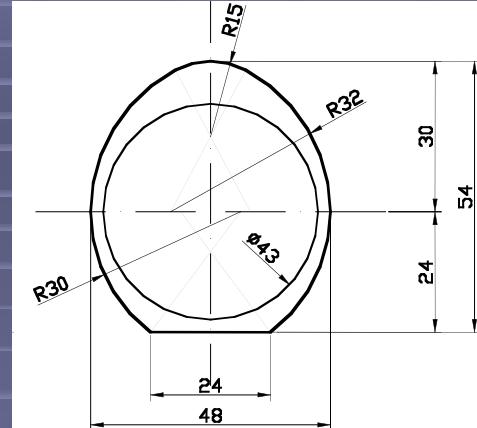


Cylindrical Dome
Larger than Super-K

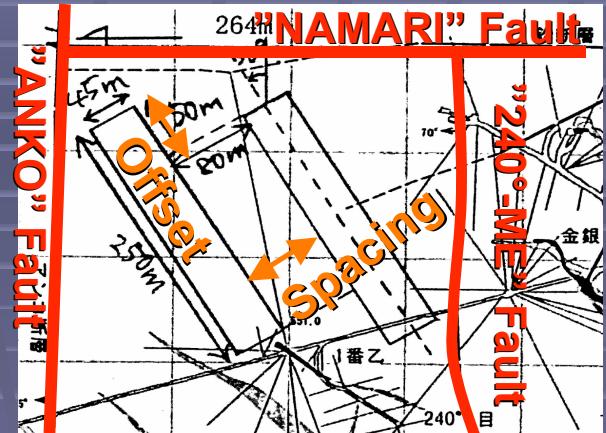


Isotropic Elastic FEM Analysis

Huge Tunnel



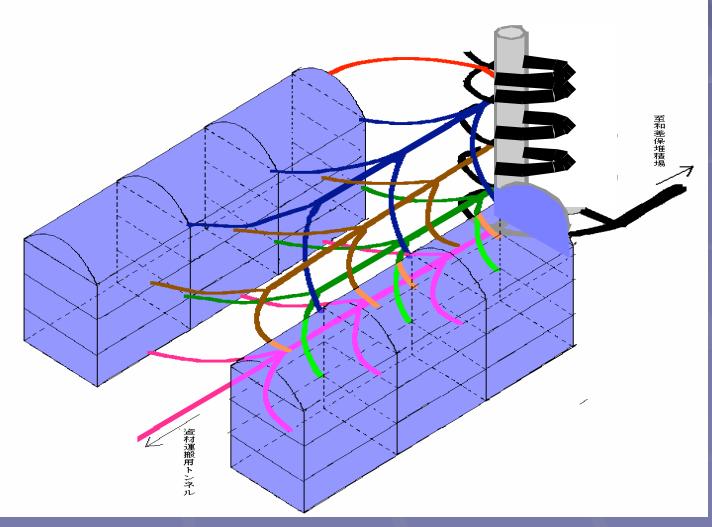
Two Parallel Tunnels



Comparison of the Hyper-K Cavern from Various View Points

Cavern Type	Multiple Domes	Single Tunnel	Two Parallel Tunnels
Construction Period & Cost	✗	○	○
Early Observation Startup	△	△	○
Observation during Maintenance	○	✗	○
Cost Performance of Detector Tank	✗	○	△
Cavern Stability	◎	○	○
Total Evaluation	✗	△	○
Size of one Cavern (m)	Height	60.0	54.0
	Width	Φ 60	48.0
	Length	---	250
Vertical Cross Section Area (m ²)	3,368	2,076	2,076
Volume of one Cavern (m ³)	152,600	1,038,000	519,000
Required No. of Caverns	7	1	2
Total Volume of Caverns (m ³)	1,068,200	1,038,000	1,038,000

Image Design of Two 250m Long Parallel Tunnels



Summary of Previous Study

Site Selection : Tochibora Mine, +480mEL~+550m EL is the most appropriate location with very competent rock condition.

Cavern Design: Two 250m Long Parallel Tunnels with Section of 2,076m² are capable of being safely excavated.

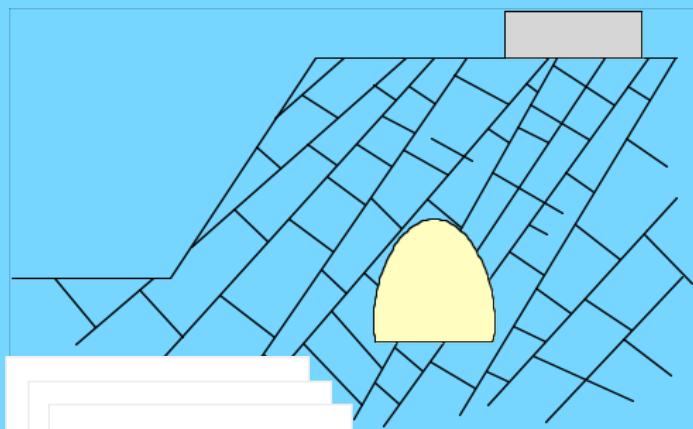
Cavern Layout : Two Parallel Tunnels as above should be Located with 80m –100m Spacing and 50m-100m Offset to avoid the poor Zone of Surrounding Faults.

In Isotropic Elastic FEM Analysis of Previous Study, Young's Modulus was empirically decreased as Jointed Rock Mass. It is Important and Necessary to Consider Numerically the Influence of Joint Orientation and Mechanical Properties.

Analysis for Jointed Rock Mass

Discontinuous Analysis

Composition of Elastic Blocks Surrounding Joints

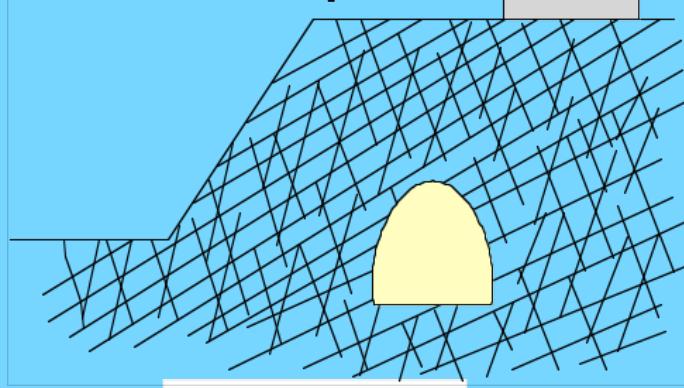


Key Block

Distinct Element Method
(DEM)

Equivalent Continuum Analysis

Anisotropic Young's Modulus Considering Joint Orientation and Mechanical Properties



Damage Tensor
Crack Tensor

- Characteristics of Joint Orientation
- Mechanical Properties of Joint and Rock Core
- Mechanical Properties of Support such as Cable Bolt

Investigation of Jointed Rock Mass

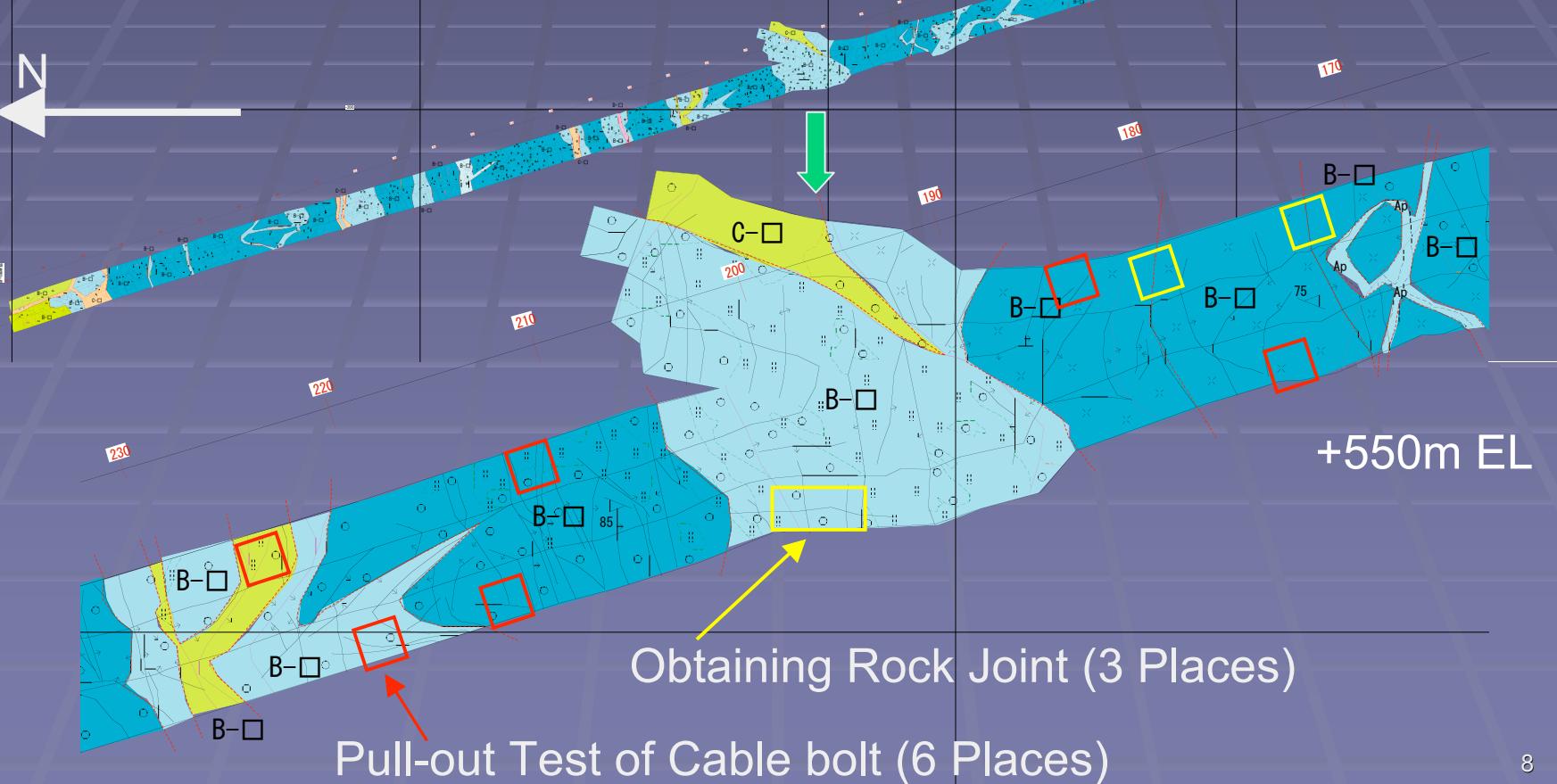
Rock Classification

- [Blue Box] B Very Good
- [Light Blue Box] CH Good
- [Yellow Box] CM Medium

Rock Types

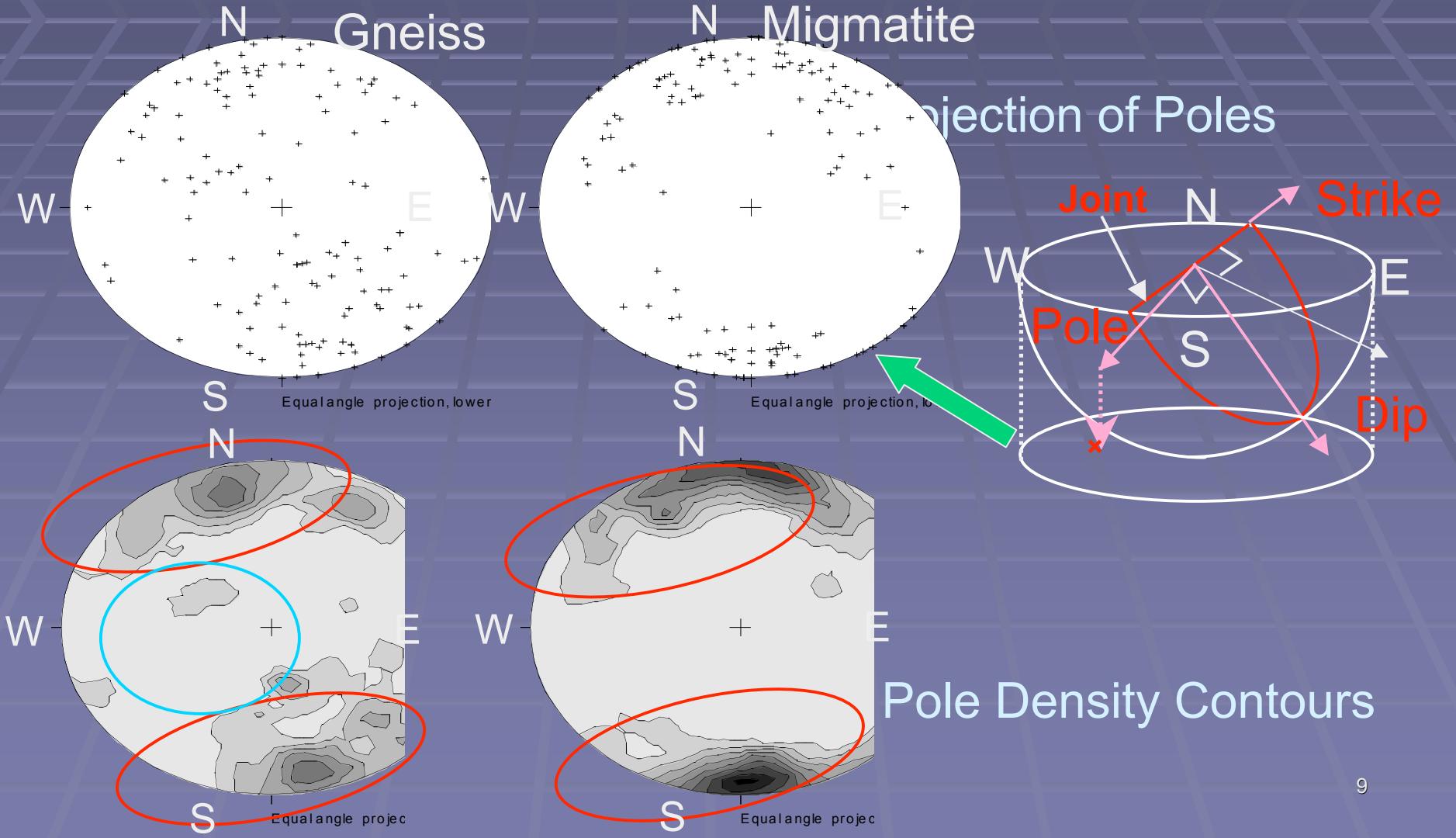
- [Cross Pattern] Gneiss
- [Open Circle] Migmatite

Measurement of Joint Orientation
in this Existing Tunnel

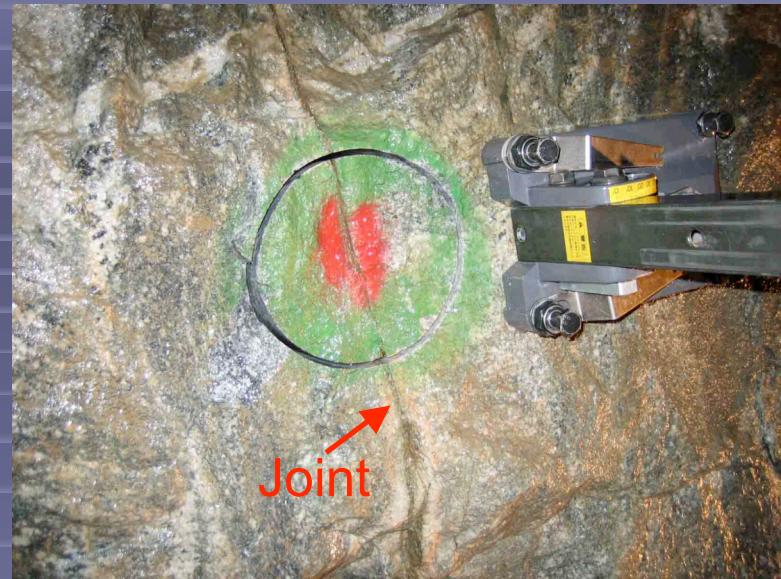


Investigation of Joint Orientation

- Major Joint Set : Strike E-W and Dip $\pm 70 \sim 90^\circ$
- Another Joint Set : Strike NE-WS and Dip $\pm 40 \sim 50^\circ$



Situation of Obtaining In-Site Rock Joints



Joint Mechanical Properties

Direct Shear Test of Rock Joints

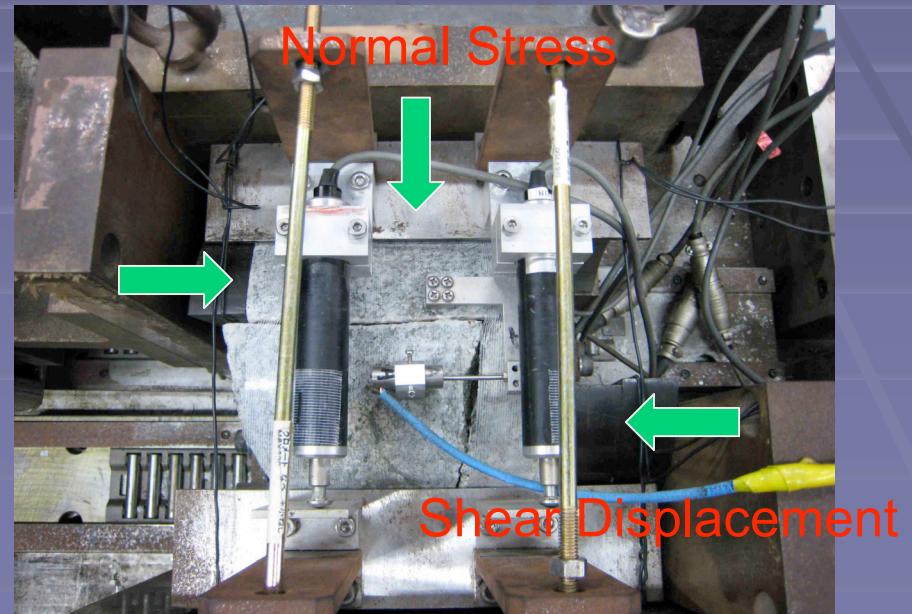
- Joint Deformability Parameters such as Normal and Shear Stiffness, Dilatancy Angle
- Joint Shear Strength such as Cohesion and Internal Friction Angle



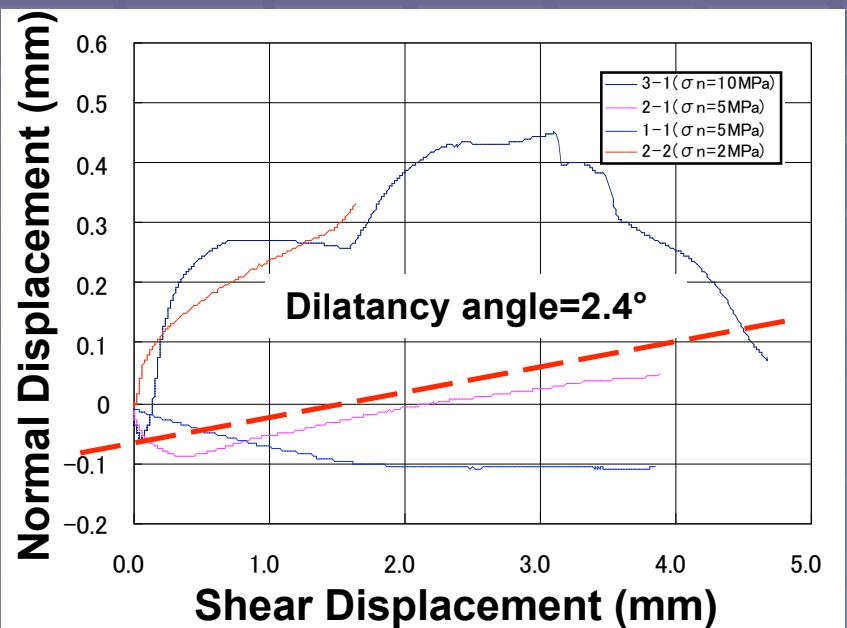
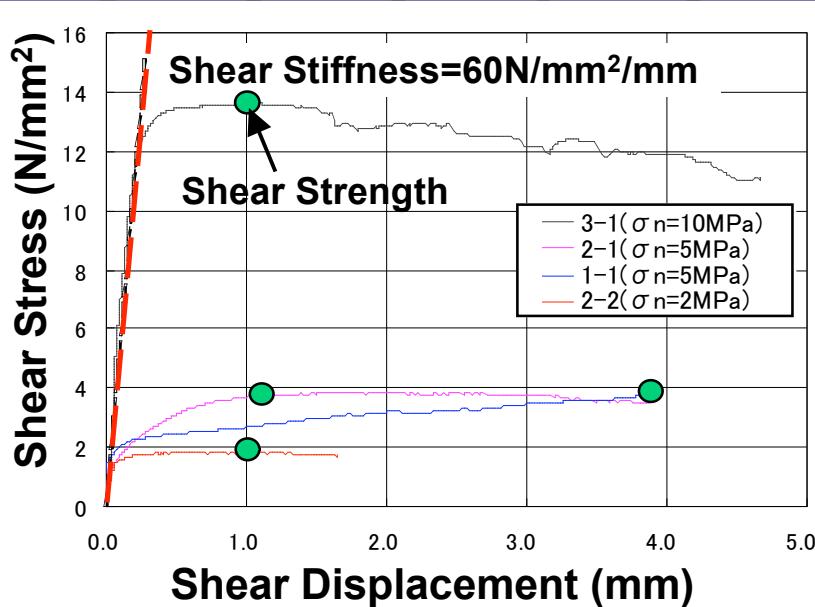
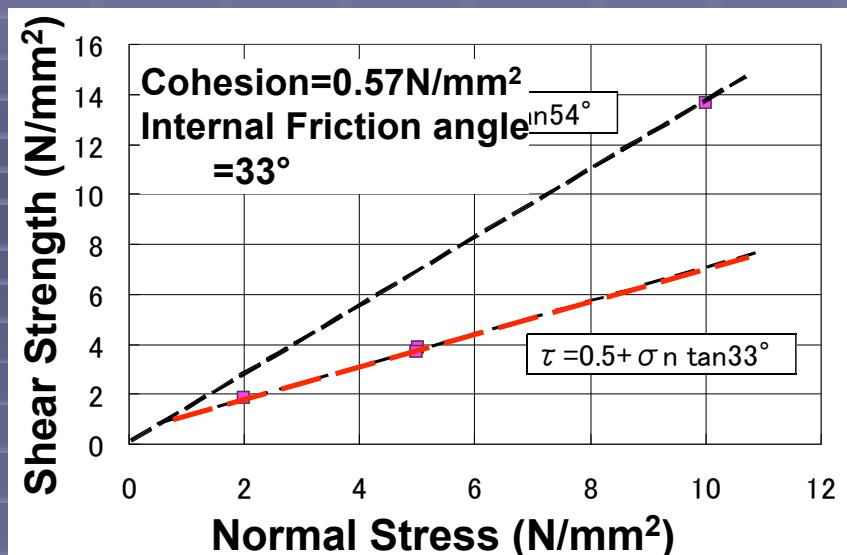
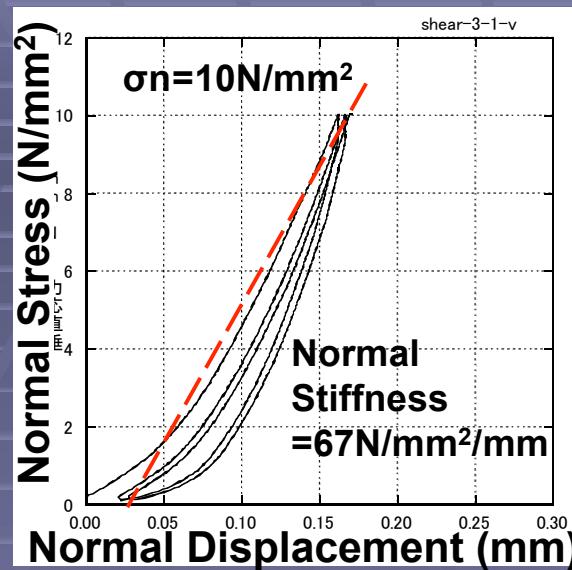
Rock Joint Specimen
with extensometers



Shear Test Equipment
(Normal and Shear load are 1MN)



Results of Direct Shear Test



Pull-Out Test of Two Type Cable Bolts

Economical Support System should be used

- Usual Support System for Large Cavern is Rock Anchor → **Expensive**
- Proposed Support System is Rock Bolt and Cable Bolt → **Economical**
- Special Cable Bolt with Dimples has very high Strength
- Mechanical Properties of Cable bolt was estimated by Pull-Out Test

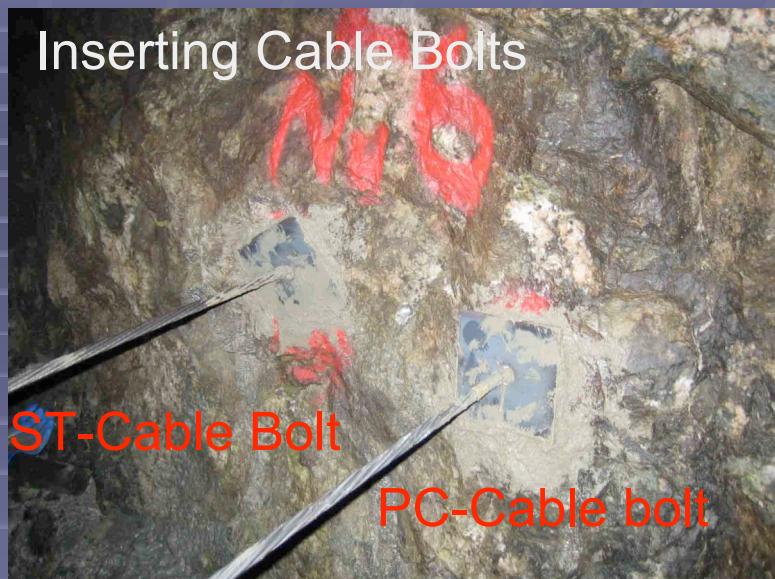
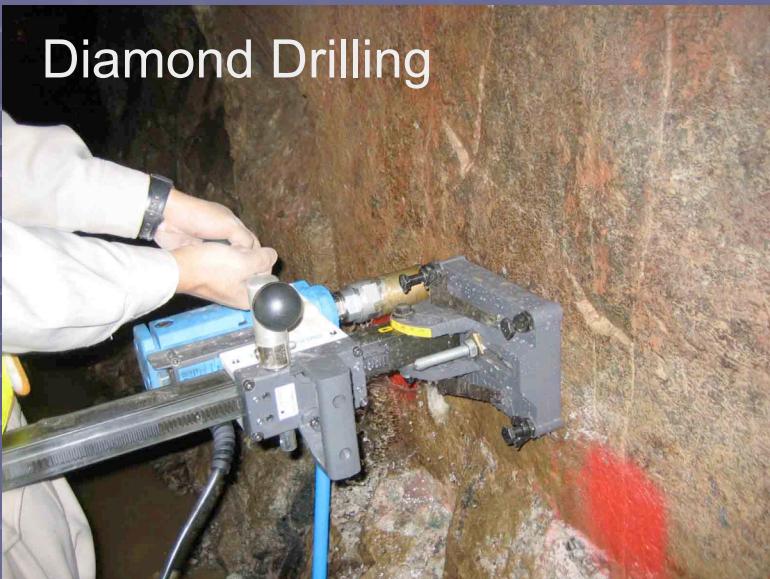
Usual Cable Bolt without Dimples
(PC-Cable Bolt)



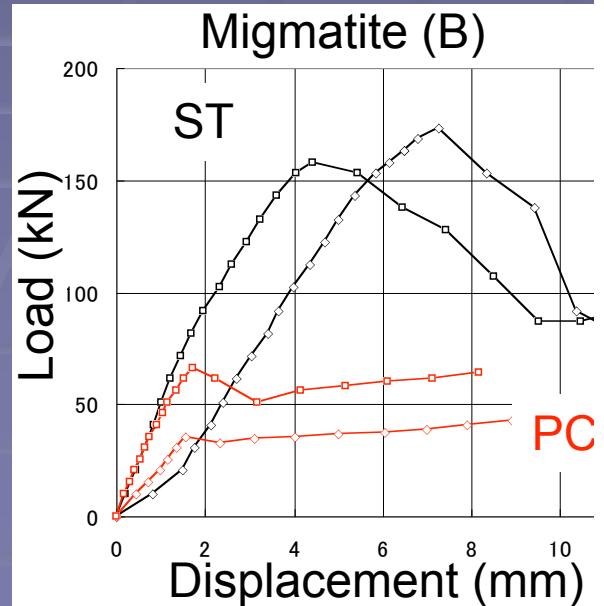
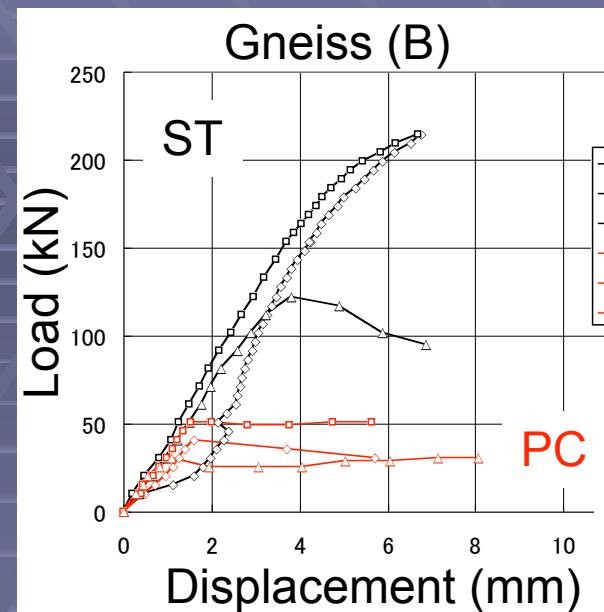
Special Cable Bolt with Dimples
(ST-Cable Bolt)



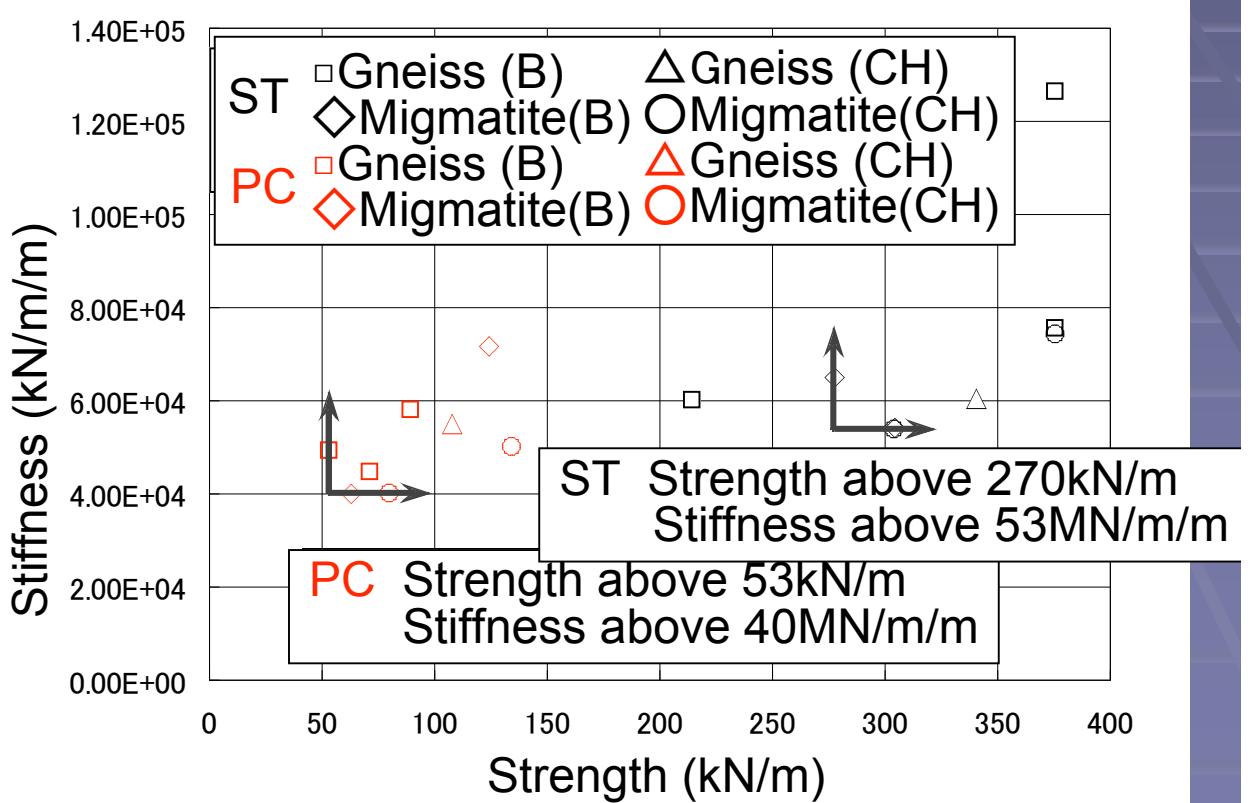
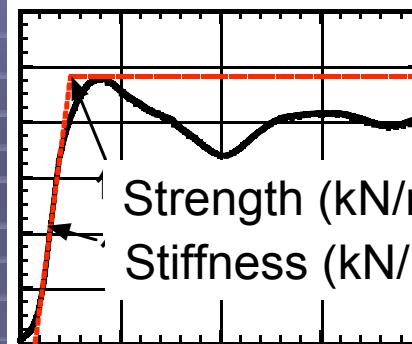
Situation of Pull-Out Tests



Results of Pull-Out Tests



Cable bolt model



Mechanical Properties

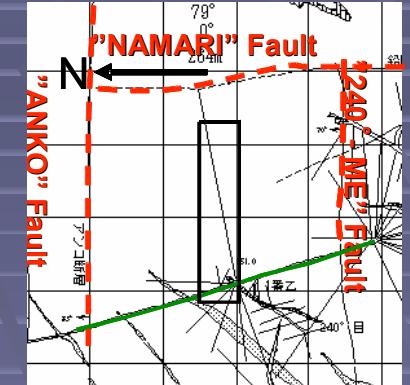
	Properties
Rock Mass Same as Intact Rock	Young's Modulus=64.3 kN/mm ² Poisson's Ratio=0.25 Density=0.26NM/m ³
Joint	Normal Stiffness=67N/mm ² /mm Shear Stiffness=60N/mm ² /mm Dairatancy Angle=2.4° Cohesion=0.57N/mm ² Internal Frictional angle=33°
ST-Cable Bolt	Shear Strength= 270kN/m Shear Stiffness=53MN/m/m
PC-Cable Bolt	Shear Strength= 53kN/m Shear Stiffness=40MN/m/m

Mechanical Properties of Intact Rock Core	Migmatite	Gneiss
Compressive Strength (N/mm ²)	191	176
Young's Modulus (kN/mm ²)	60.4	64.3
Poisson's Ratio	0.24	0.26
Density (MN/m ³)	0.027	0.027

Discontinuous Analysis by DEM

DEM Analysis is Performed to Establish the Behavior of Jointed Rock Mass and the Effect of Support System.

Cavern Direction is East and West



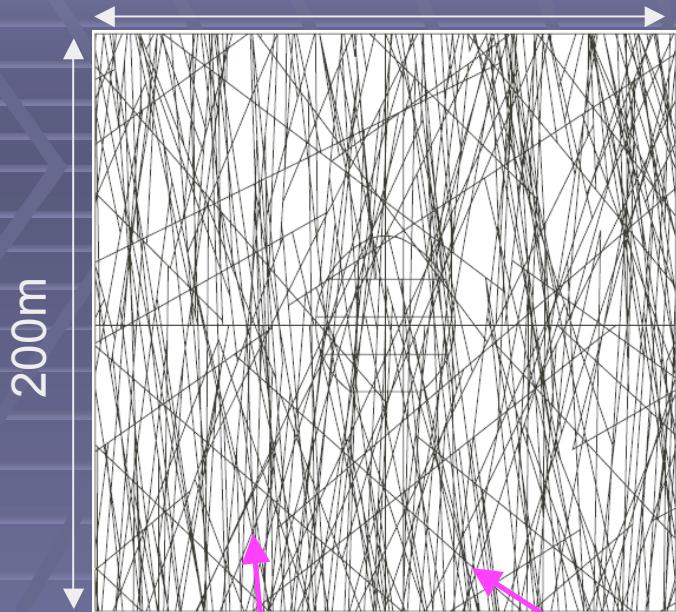
Cavern Type and Direction

Analysis Cases

	Support	In-Situ Stress
Case 1	Without Support	
Case 2	Rock Bolt (Length=6m :Space=2m) Double PC-Cable Bolt (Length=15m :Space=2m)	Isotropic Stress $\sigma_H = \sigma_V = 14.4$ (N/mm ²) (Overburden:500m)
Case 3	Rock Bolt (Length=6m :Space=2m) Double ST-Cable Bolt (Length=15m :Space=2m)	

Procedure of Analysis

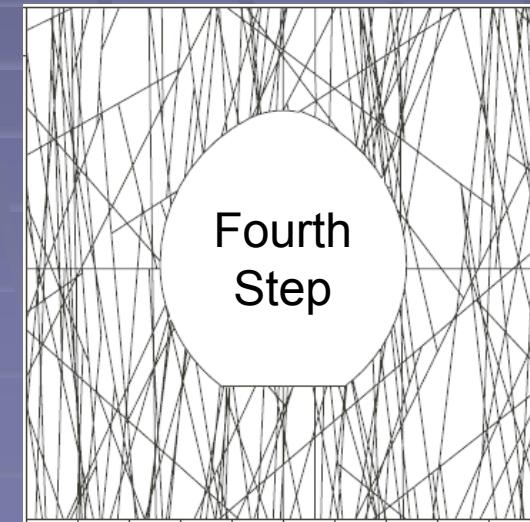
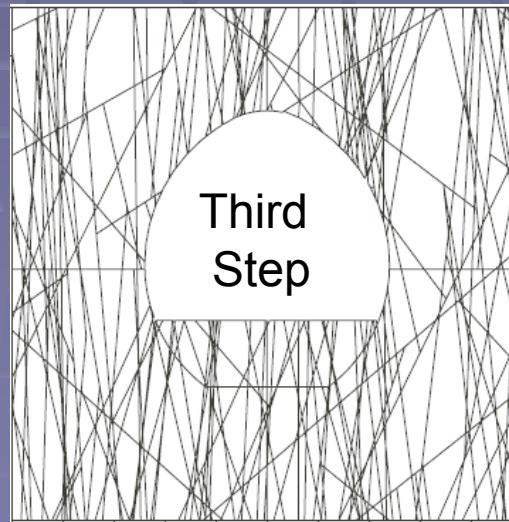
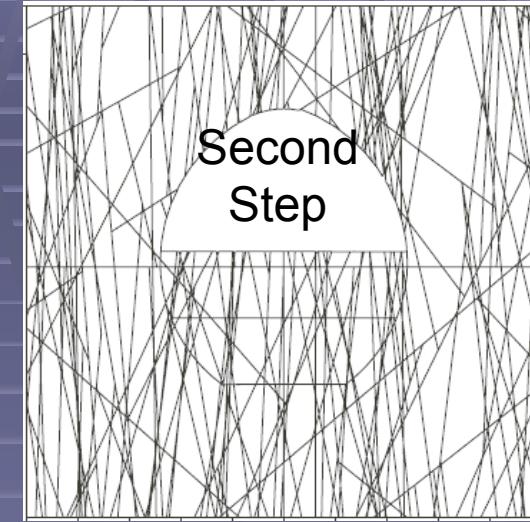
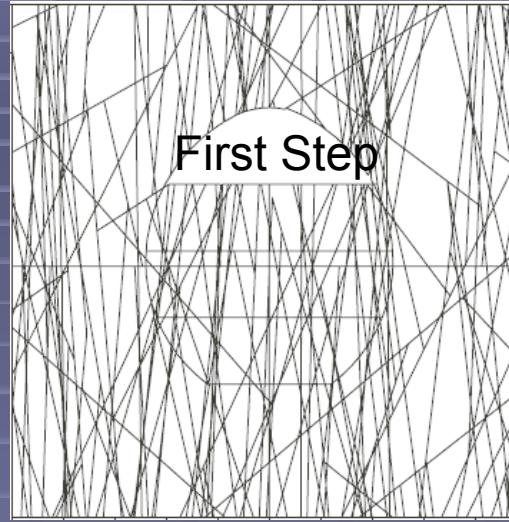
200m



Strike E-W
Dip $\pm 70 \sim 90^\circ$
Strike NS-WS
Dip $\pm 40 \sim 50^\circ$

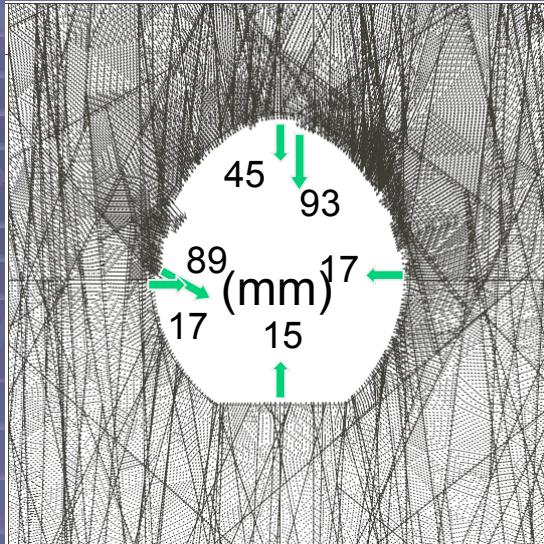
Analysis Model

Joints are Generated
Statistically According to
the Joint Orientation

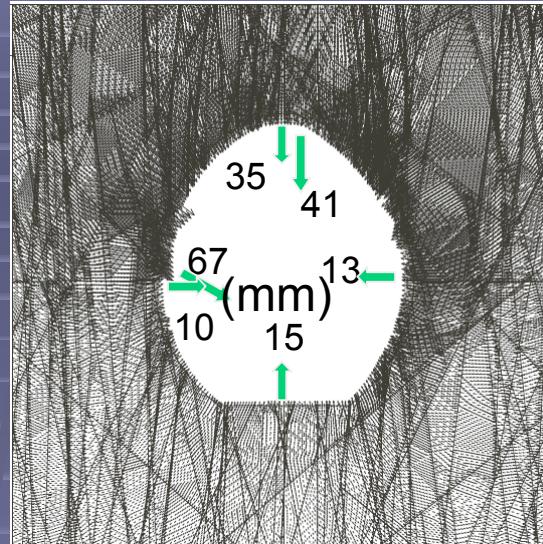


Establishing Support System
after Each Excavation Step

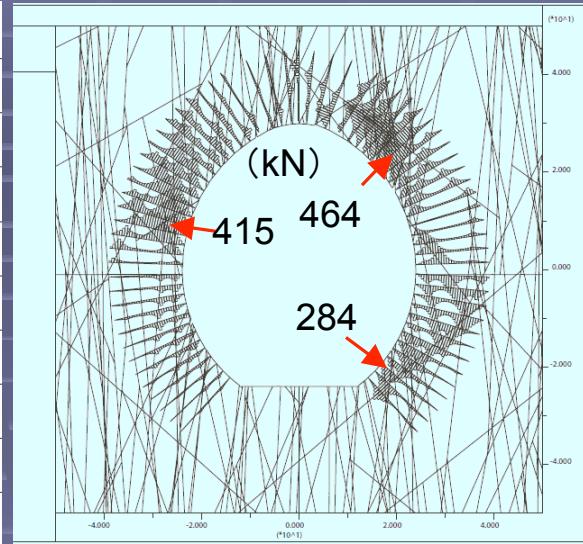
Displacement Vector and Cable Axial Force



Case 1:Without Support

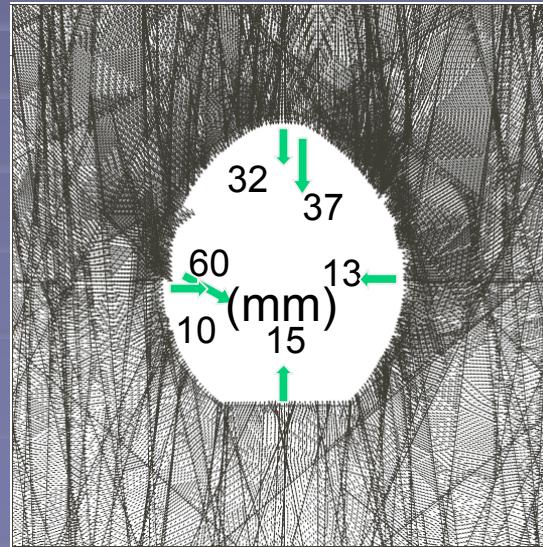


Case 2:RB+PC-Cable Bolt (Double)

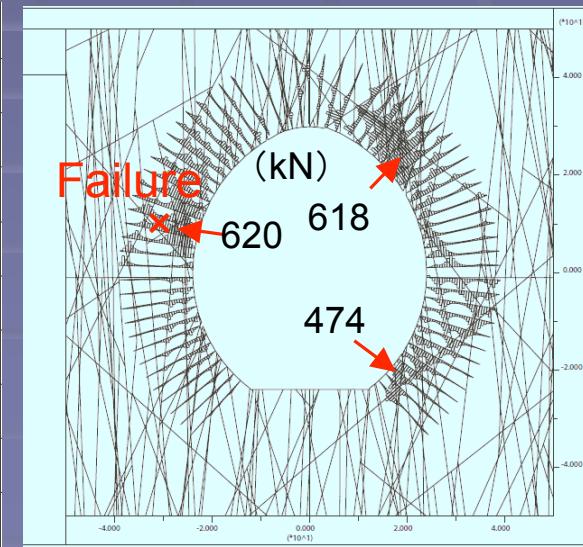


Displacement of Right and Left Side Wall are nearly same because of Symmetrical Joint Dip Angle ($\pm 70 \sim 90^\circ$).

Displacement of Case-3 is smaller than Case-2 because of Support Effect



Case 3: RB+ST-Cable Bolt (Double)



Equivalent Continuum Analysis by Crack Tensor

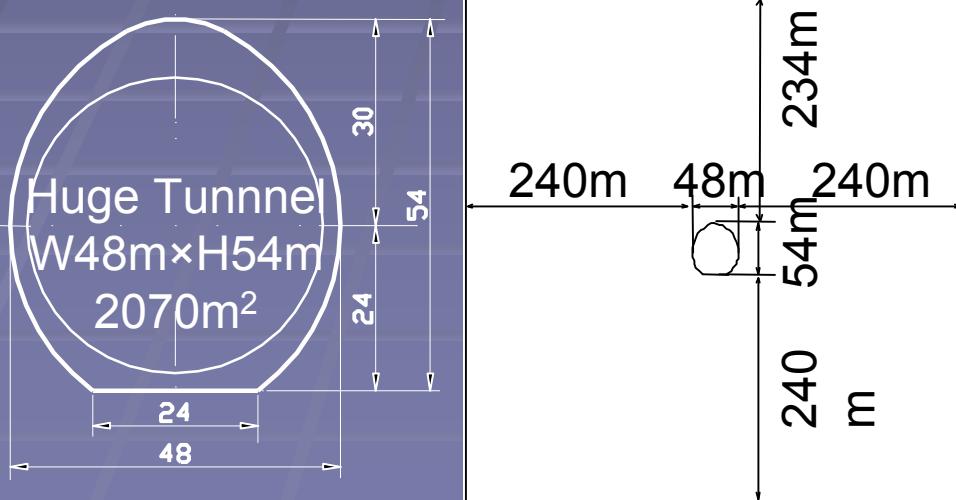
Crack Tensor Analysis is Performed to Estimate the Relation between Tunnel Direction and Joint Orientation.

In-Situ Stress is Isotropic

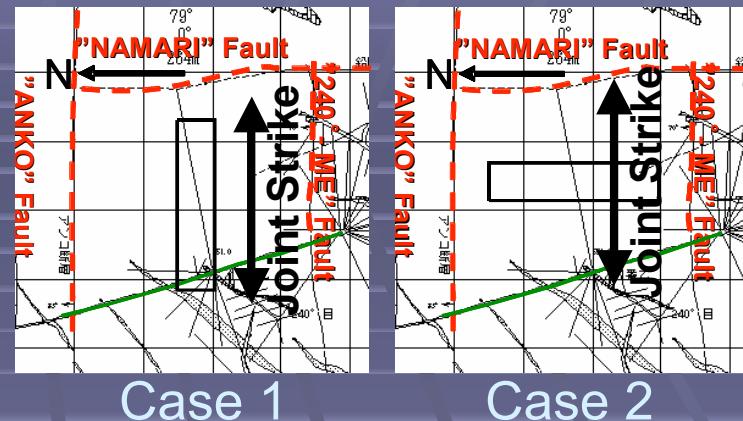
$$\sigma_H = \sigma_V = 14.4 \text{ (N/mm}^2\text{)}$$

Case 1:Cavern Direction is East and West, parallel Joint Strike

Case 2:Cavern Direction is North and South, right-angled Joint Strike

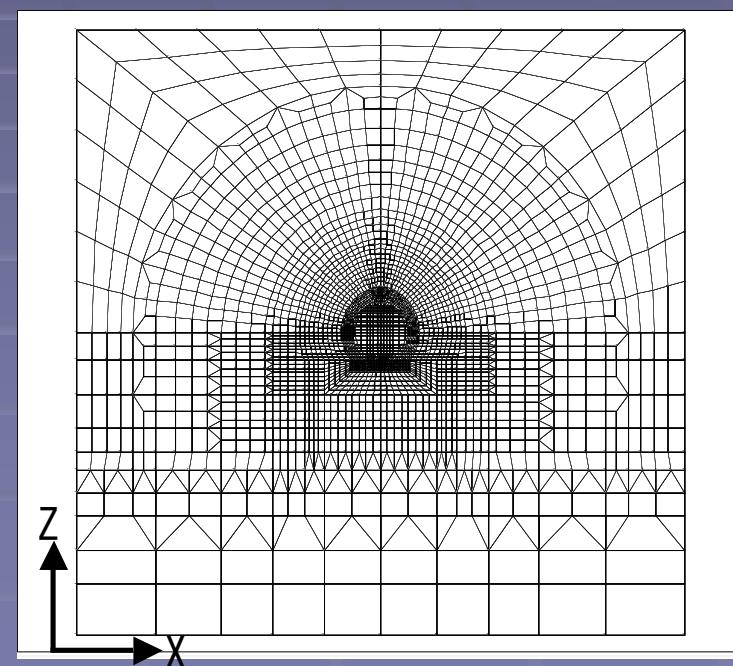


Cavern Type and Region (528m×528m)



Case 1

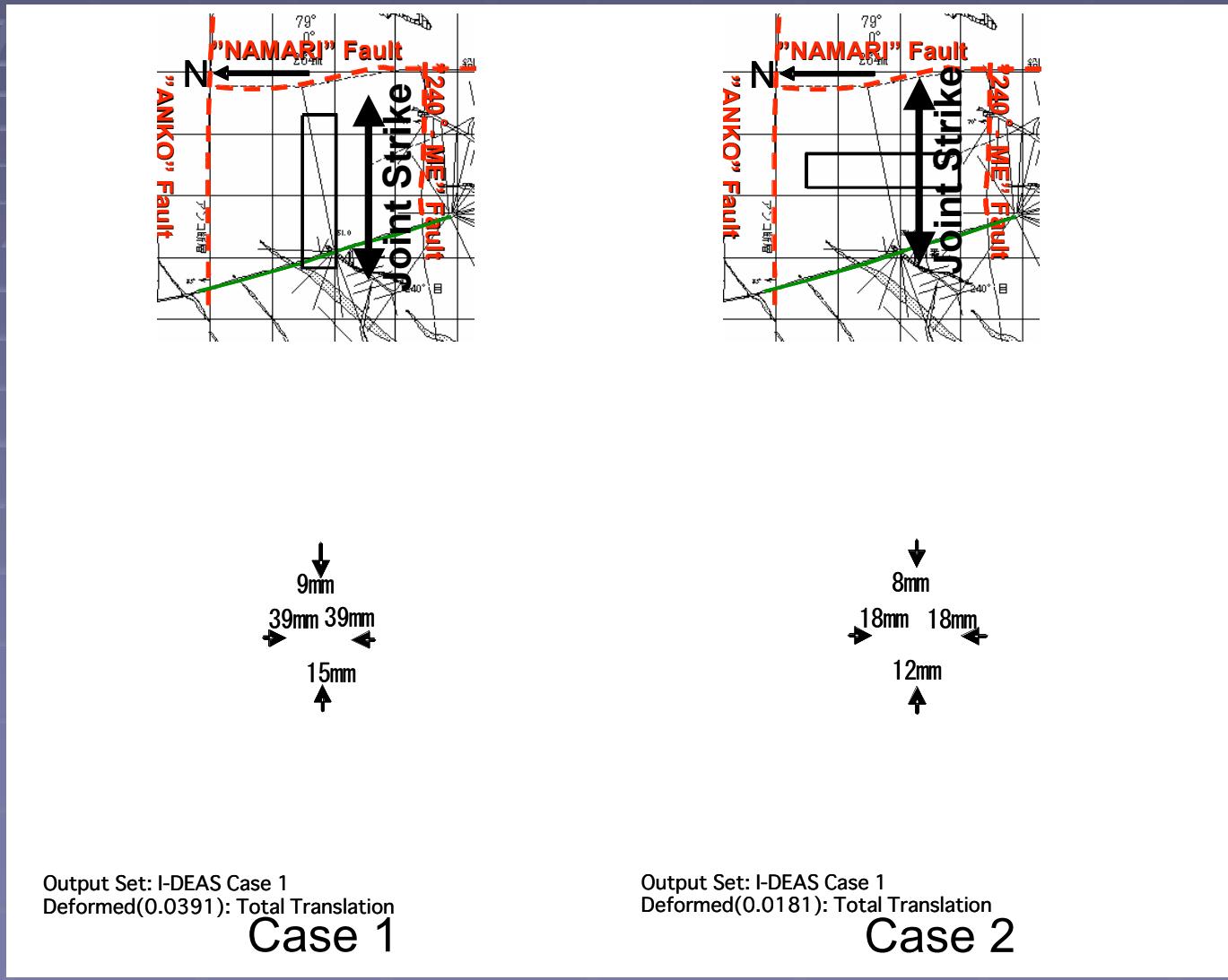
Case 2



Model

Displacement

Side Wall Displacement of Case 1 is 2 times Larger than Case 2 because of influence of Joint Strike Direction.



Summary

Joint Orientation : At Proposed Site in Tochibora Mine, Major Joint Set Strike Direction is E-W and Dip Angle is $\pm 70 \sim 90^\circ$

Joint Properties : Normal and Shear Stiffness, Shear Strength are Estimated.

Cable Bolt Properties : Shear Strength and Stiffness of ST and PC Cable Bolt are Estimated. Shear Strength of ST-Cable Bolt is 5 Times Higher than PC-Cable Bolt. ST-Cable Bolt is very Effective Support.

Results of Analysis : Discontinuous and Equivalent Continuum Analysis are able to Estimate the Effect of Rock Support System and the Anisotropic Behavior of Jointed Rock Mass. Joint Orientation is very Important factor to decide the Cavern Axis.

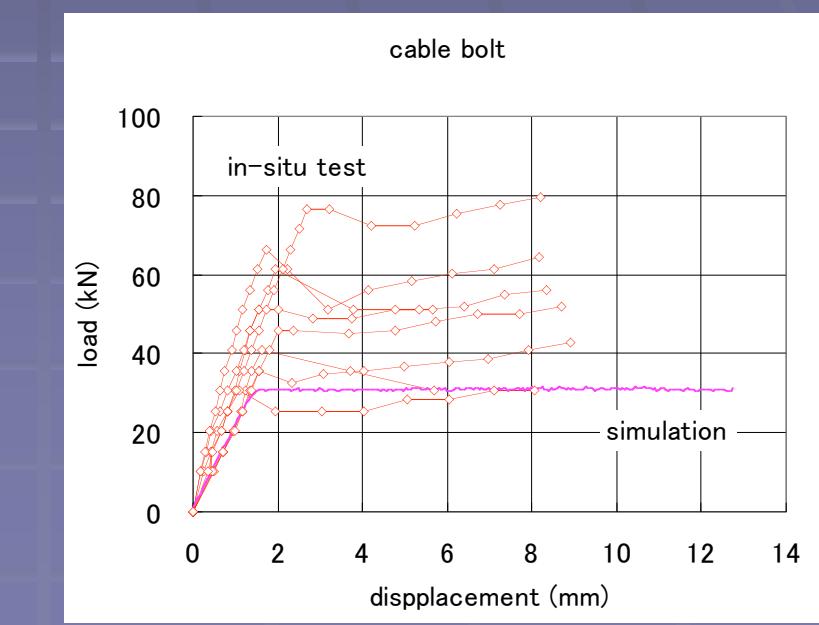
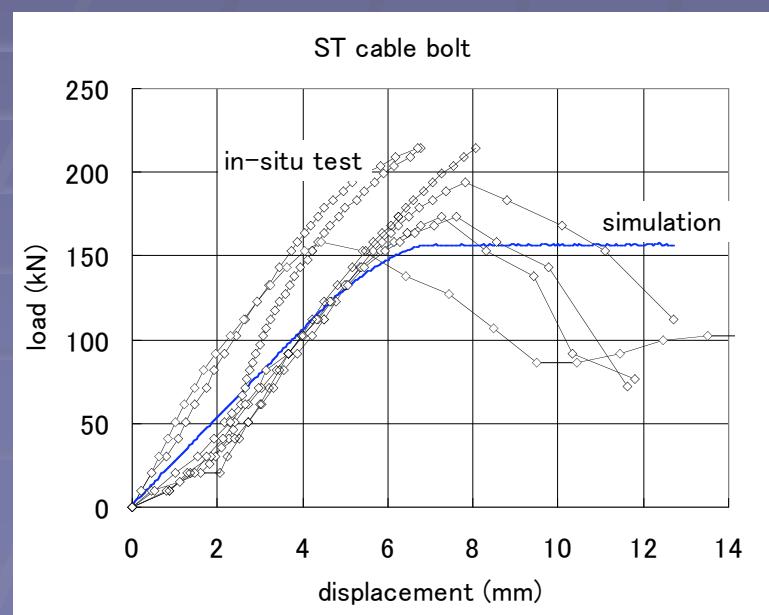
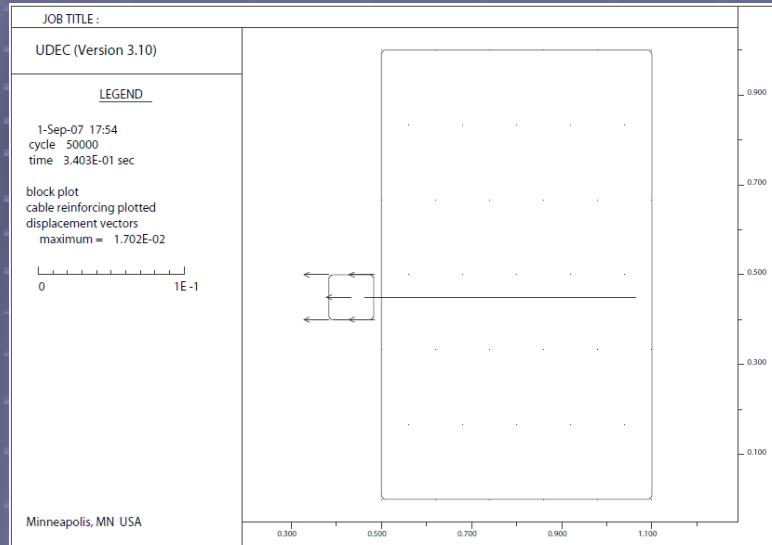
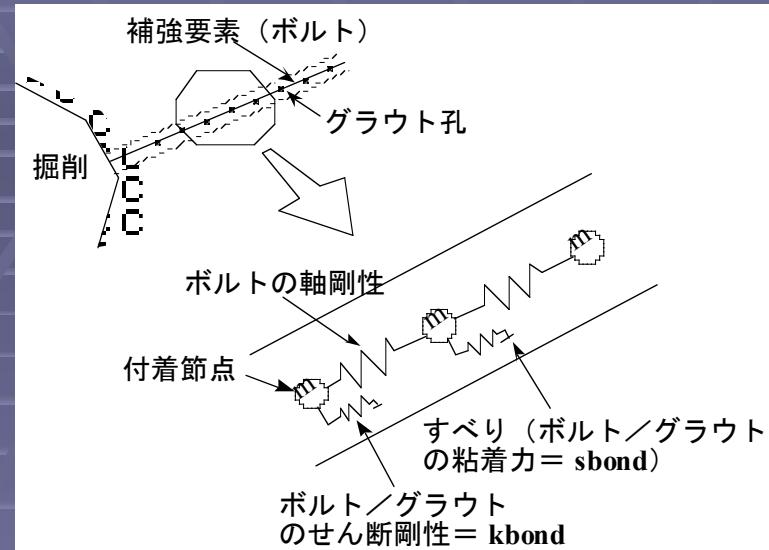
Further Investigation : It is Necessary for Accurate Joint Orientation to investigate in Different Direction Tunnel or Bore Hole.

Measurements of In-Situ Initial Stresses and In-Situ Tests on Rock Mass Deformability are indispensable.



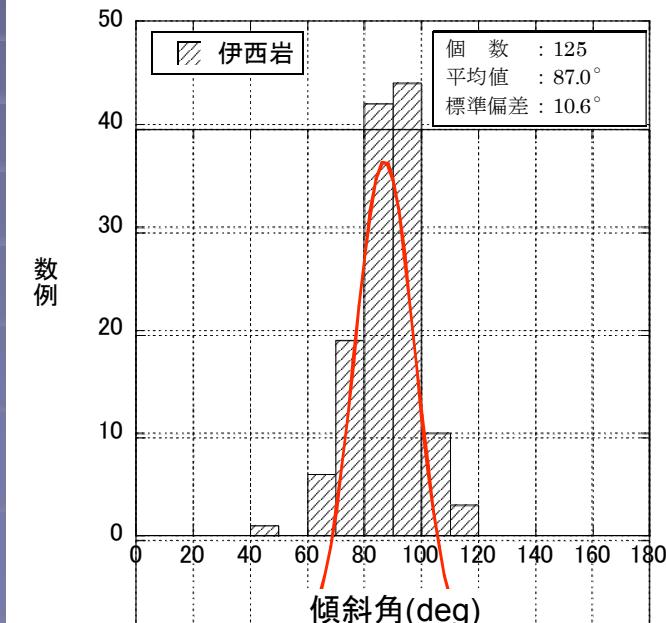
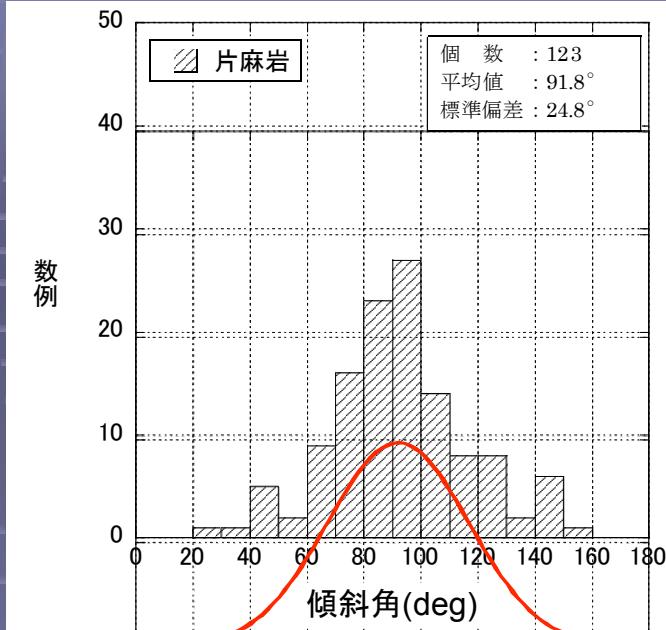
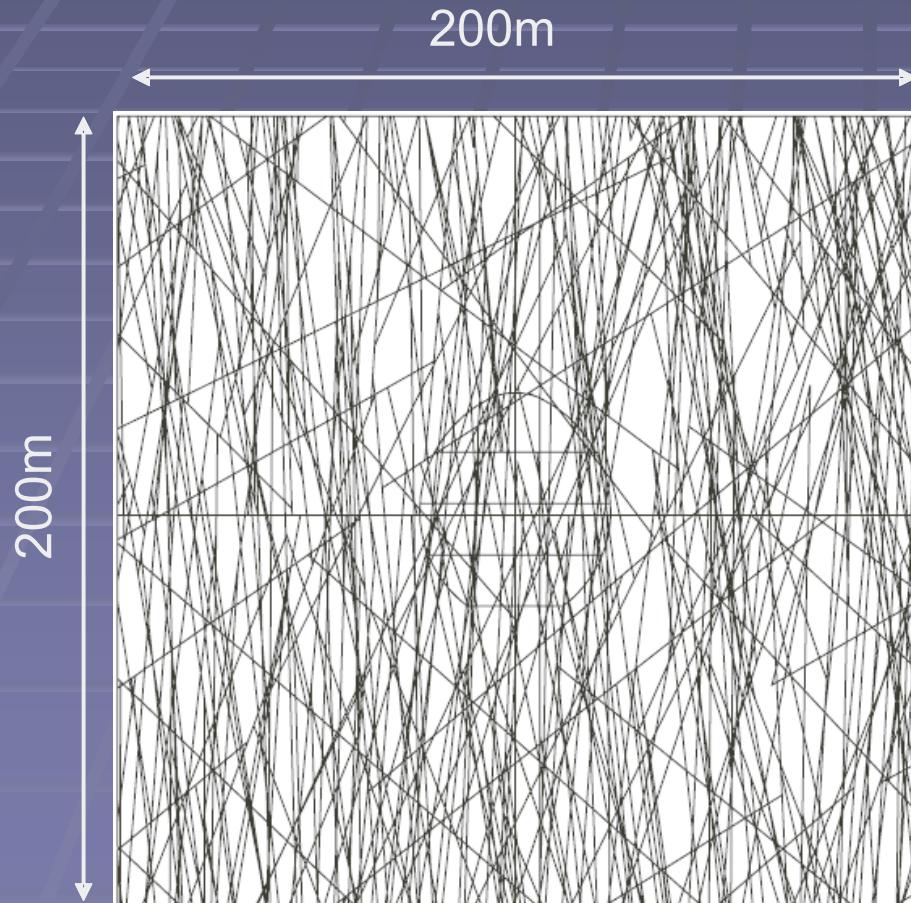
END

ボルトの引き抜き試験の解析



空洞の安定解析

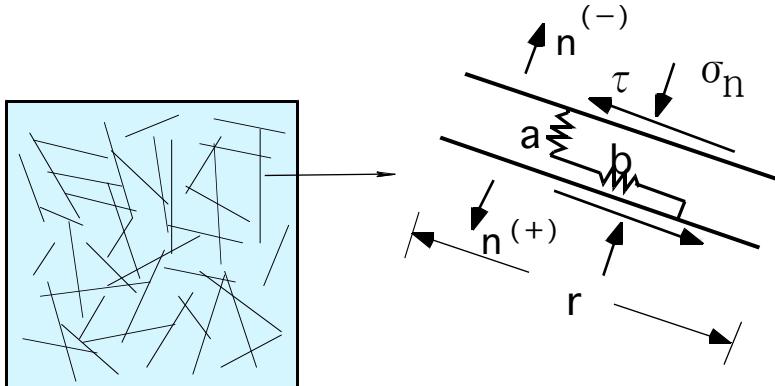
南北の鉛直面に亀裂傾斜を投影し、統計的に亀裂を発生させてモデルを作成



クラックテンソルによる解析手法の概要

クラックテンソルによる不連続性岩盤の巨視的な応力とひずみ関係

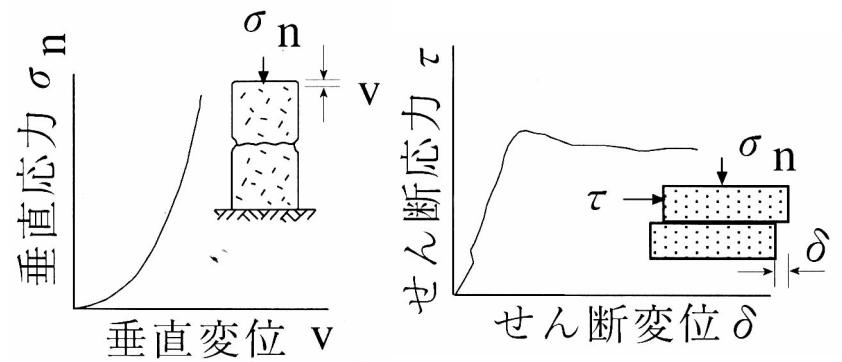
$$\varepsilon_{ij} = \left[\frac{1}{E} \left\{ (1 + \nu) \delta_{ik} \delta_{jl} - \nu \delta_{ij} \delta_{kl} \right\} + \left(\frac{1}{h} - \frac{1}{g} \right) F_{ijkl} + \frac{1}{4g} (\delta_{ik} F_{jl} + \delta_{jk} F_{il} + \delta_{il} F_{jk} + \delta_{jl} F_{ik}) \right] \sigma_{kl}$$



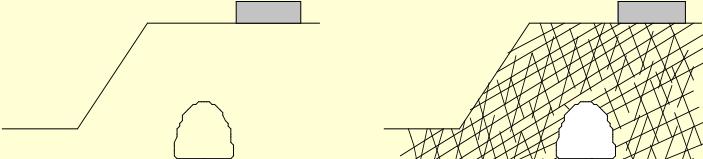
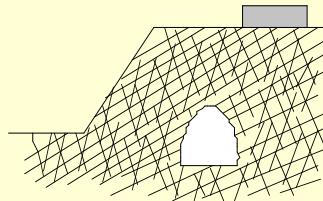
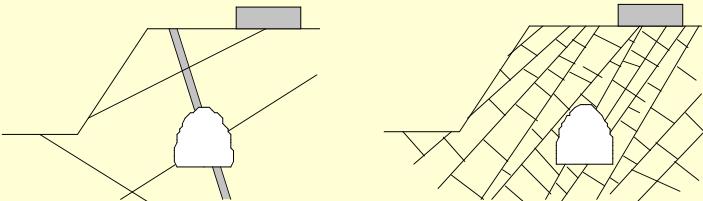
多数の不連続面を含む岩盤 a : 垂直方向のスフリンク
b : せん断方向のスフリンク

↓ クラックテンソル 垂直剛性 , せん断剛性
(Fij, Fijkl) (h, g)

- 岩盤基質部の弾性係数、ボアン比 (E, ν)
- 不連続面の垂直剛性とせん断剛性に関するパラメータ (h, g)
- 不連続面の幾何学特性を表す 2階、4階のクラックテンソル (Fij, Fijkl)



不連続性岩盤を対象とした解析手法

解析手法		亀裂のモデル化	適用岩盤の概念	
F E M 連 続 体 解 析	等方	<u>弾性解析</u> × 亀裂の存在を岩盤の物性低下で考慮	 <p>亀裂がない、または、ランダムな方向性の無数の亀裂を有する岩盤</p>	
	等価	弾塑性解析		
		非線形粘弾性解析		
不 連 続 体 解 析	DEM	<u>NAPIS</u> <u>MBC</u> <u>EQR</u> 複合降伏モデル <u>クラックテンソル</u> 損傷テンソル	○ 無数にある亀裂の効果を等価な連続体で表現。 「亀裂の開口」と「亀裂の卓越方向に沿った変形」を剛性低下で表現可能。	 <p>方向性を持った無数の亀裂を有する岩盤</p>
		ジョイント要素	○ 個々の亀裂を解析メッシュ上でモデル化。 「亀裂の開口」と「亀裂の卓越方向に沿った変形」を表現可能（キー ブロック解析を除く）。	 <p>比較的少数の特定の長い亀裂を有する岩盤や有限個の亀裂に囲まれた岩盤ブロック</p>
		RBSM		
		DEM		
		キー ブロック解析		
		DDA		
		マニホールド法		

1.原位置岩盤のクラックテンソルの決定

クラックテンソルの算定

■三次元の N_{ij} , N_{ijkl}

$$\begin{bmatrix} N_{11} & N_{12} & N_{13} \\ N_{22} & N_{23} & \\ Sym. & N_{33} \end{bmatrix} = \begin{bmatrix} 0.238 & -0.055 & -0.008 \\ & 0.630 & -0.012 \\ & Sym. & 0.132 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} N_{1111} & N_{1122} & N_{1133} & N_{1112} & N_{1123} & N_{1131} \\ N_{2222} & N_{2233} & N_{2212} & N_{2223} & N_{2231} & \\ N_{3333} & N_{3312} & N_{3323} & N_{3331} & & \\ N_{1212} & N_{1223} & N_{1231} & & & \\ Sym. & N_{2323} & N_{2331} & & & \\ & N_{3131} & & & & \end{bmatrix} = \begin{bmatrix} 0.120 & 0.089 & 0.029 & -0.023 & -0.007 & -0.002 \\ 0.493 & 0.048 & -0.027 & -0.008 & -0.004 & \\ 0.055 & -0.005 & 0.003 & -0.002 & & \\ 0.089 & -0.004 & -0.007 & & & \\ 0.048 & -0.005 & & & & \\ Sym. & & & 0.029 & & \end{bmatrix} \quad (2)$$

■二次元断面上の N_{ij} , N_{ijkl}

$$\begin{bmatrix} N_{11} & N_{13} \\ Sym. & N_{33} \end{bmatrix} = \begin{bmatrix} 0.800 & 0.029 \\ Sym. & 0.200 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} N_{1111} & N_{1133} & N_{1131} \\ N_{3333} & N_{3331} & \\ Sym. & N_{3131} \end{bmatrix} = \begin{bmatrix} 0.716 & 0.084 & 0.024 \\ 0.116 & 0.006 & \\ & 0.084 & \end{bmatrix} \quad (4)$$

■ F_0 の算定

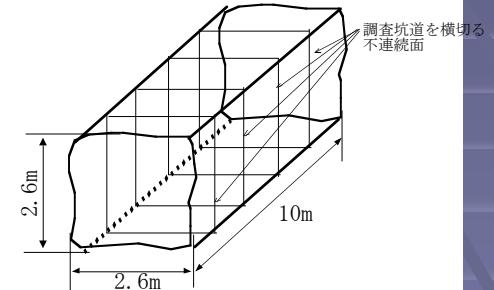
- ・調査坑道10mあたり4本の不連続面を想定
- ・不連続面の寸法（等価円の直径r）
不連続面の面積 : $S=2.6m \times 2.6m=6.76m^2$ (5)

$$r = 2\sqrt{S/\pi} = 2\sqrt{6.76/\pi} = 2.9m \quad (6)$$

・ F_0 の算定

$$\begin{aligned} F_0 &= \frac{\pi}{4V} \sum_{k=1}^M \left(\cdot^{(k)} \right) \\ &= \frac{\pi}{4 \times 2.6 \times 2.6 \times 10} 2.9^3 \times 4 \\ &= 1.13 \end{aligned} \quad (7)$$

$$\therefore F_0 = 1.0 \quad (8)$$



■二次元断面上の F_{ij} , F_{ijkl}

$$F_{ij} = F_0 N_{ij}, F_{ijkl} = F_0 N_{ijkl}$$

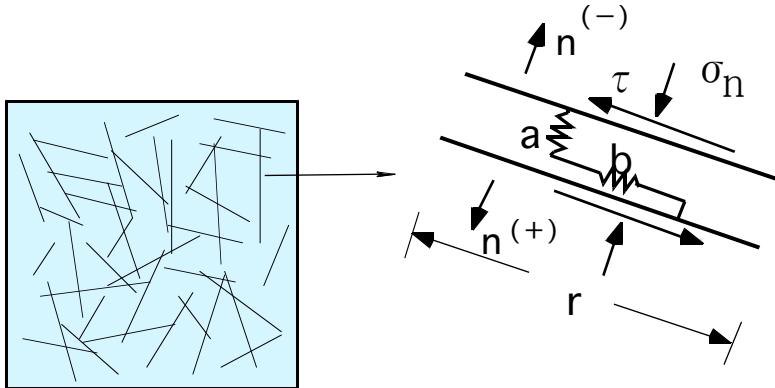
$$\begin{bmatrix} F_{11} & F_{13} \\ Sym. & F_{33} \end{bmatrix} = \begin{bmatrix} 0.800 & 0.029 \\ Sym. & 0.200 \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} F_{1111} & F_{1133} & F_{1131} \\ F_{3333} & F_{3331} & \\ Sym. & F_{3131} \end{bmatrix} = \begin{bmatrix} 0.716 & 0.084 & 0.024 \\ 0.116 & 0.006 & \\ & 0.084 & \end{bmatrix} \quad (10)$$

クラックテンソルによる解析手法の概要

クラックテンソルによる不連続性岩盤の巨視的な応力とひずみ関係

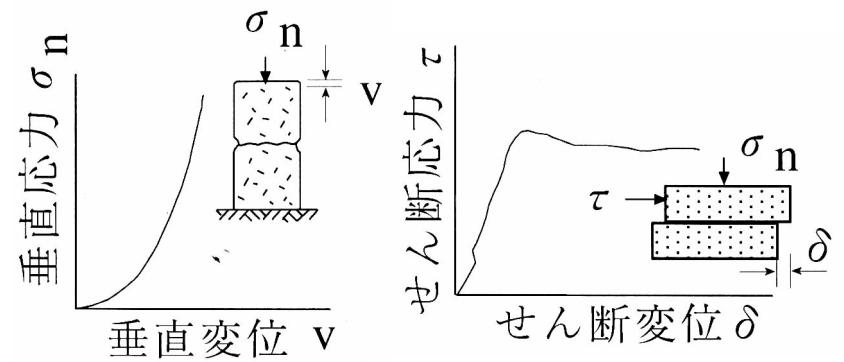
$$\varepsilon_{ij} = \left[\frac{1}{E} \left\{ (1 + \nu) \delta_{ik} \delta_{jl} - \nu \delta_{ij} \delta_{kl} \right\} + \left(\frac{1}{h} - \frac{1}{g} \right) F_{ijkl} + \frac{1}{4g} (\delta_{ik} F_{jl} + \delta_{jk} F_{il} + \delta_{il} F_{jk} + \delta_{jl} F_{ik}) \right] \sigma_{kl}$$



多数の不連続面を含む岩盤 a : 垂直方向のスループリンク
b : せん断方向のスループリンク

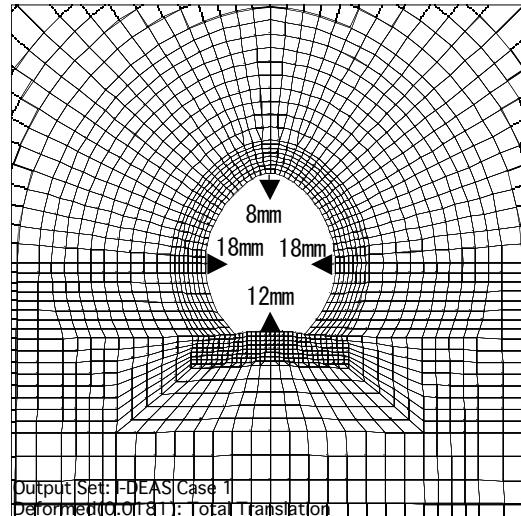
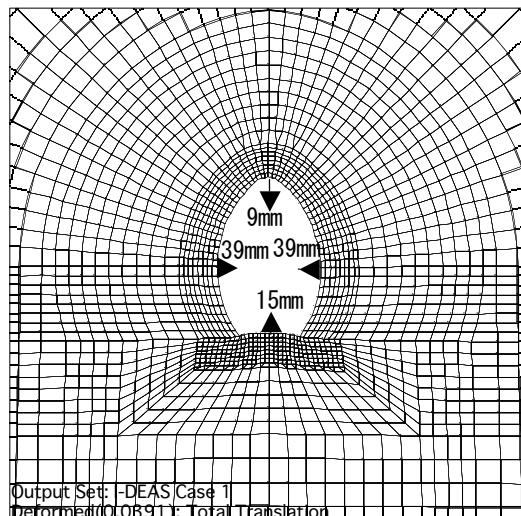
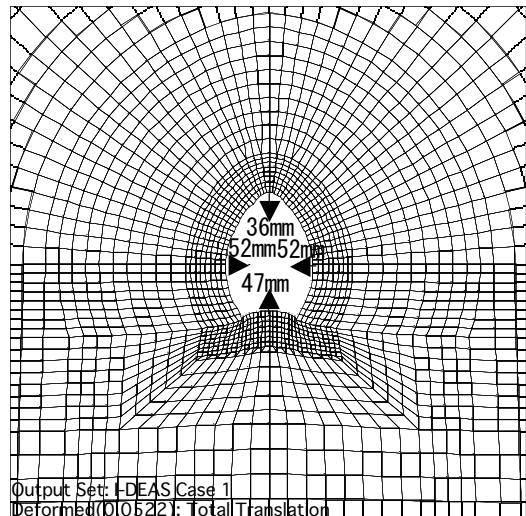
↓ クラックテンソル 垂直剛性 , せん断剛性
(F_{ij} , F_{ijkl}) (h, g)

- ・岩盤基質部の弾性係数、ボアン比 (E, ν)
- ・不連続面の垂直剛性とせん断剛性に関するパラメータ (h, g)
- ・不連続面の幾何学特性を表す 2階、4階のクラックテンソル (F_{ij} , F_{ijkl})



解析結果

等方弾性解析

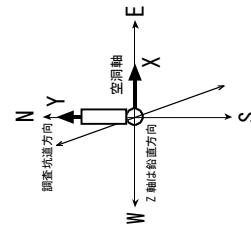


ケース 1

ケース 3

変形図（200倍）

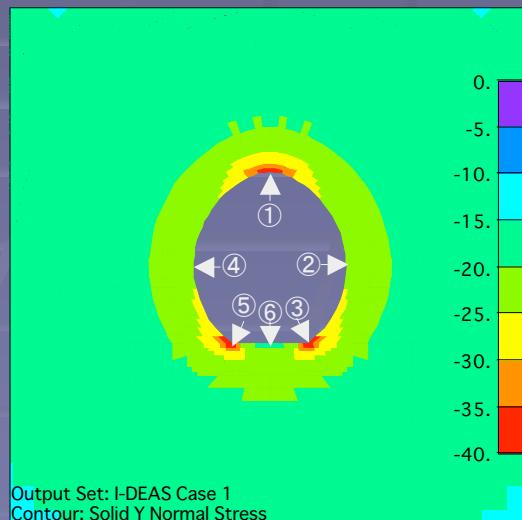
- 空洞軸を東西方向とするケース 2では、二次元断面上の不連続面が鉛直方向（Z方向）に卓越するためそれに垂直な方向となるX方向に変形が大きく生じる変形モードとなる。
- 一方、空洞軸を南北方向とするケース 3では、空洞軸方向に対して直交する不連続面が卓越するため、X Z 方向の変形は小さく、空洞軸方向の変形が大きく生じる変形モードとなる。



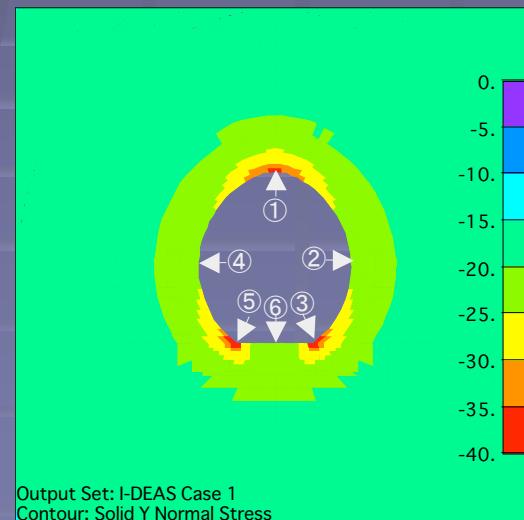
解析結果

	ケース 1	ケース 2	ケース 3
天端①	-36.18	-35.21	-35.88
右側壁②	-24.39	-23.77	-24.23
右隅角③	-36.14	-35.71	-36.21
左側壁④	-24.39	-23.69	-24.26
左隅角⑤	-36.14	-35.73	-36.18
底盤⑥	-18.65	-20.55	-19.34

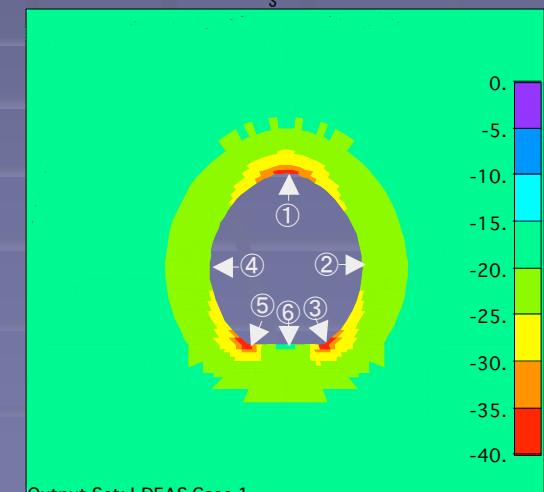
等方弾性解析



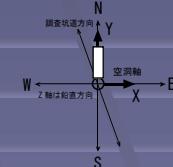
ケース 1



ケース 2
最大主応力分布 (N/mm²)



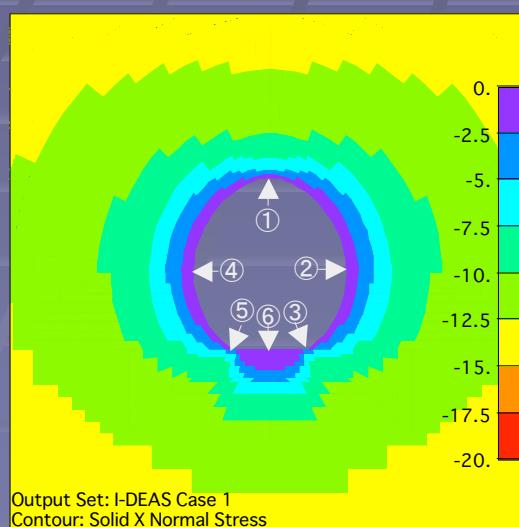
ケース 3



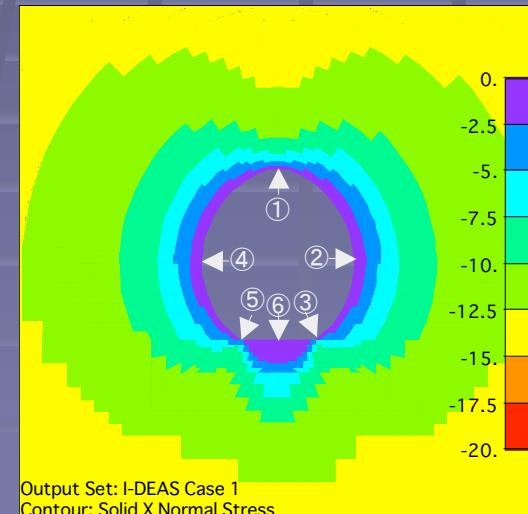
解析結果

	ケース 1	ケース 2	ケース 3
天端①	-1.49	-1.45	-1.46
右側壁②	-0.48	-0.47	-0.47
右隅角③	-4.80	-5.10	-5.06
左側壁④	-0.48	-0.46	-0.48
左隅角⑤	-4.80	-4.95	-5.14
底盤⑥	-0.03	-0.03	-0.03

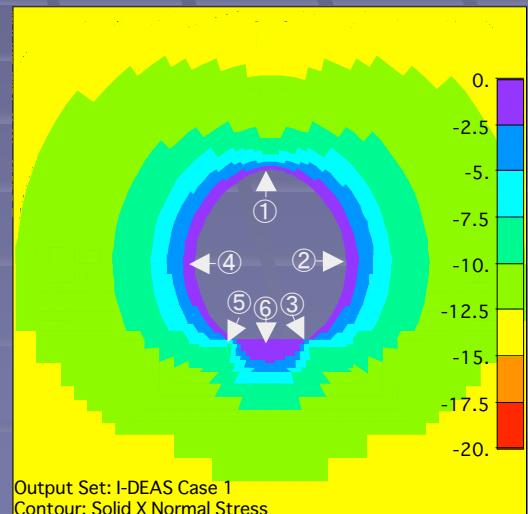
等方弾性解析



ケース 1



ケース 2

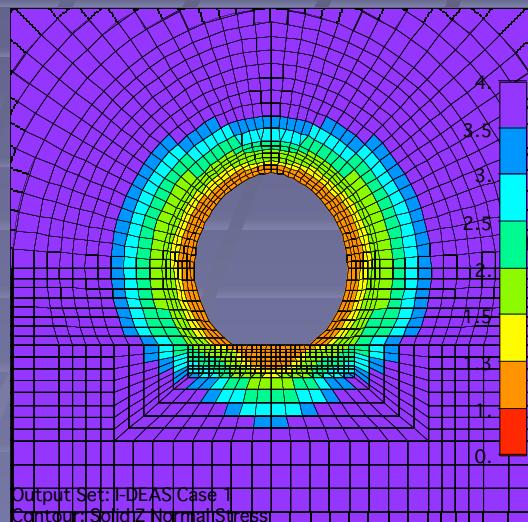


ケース 3

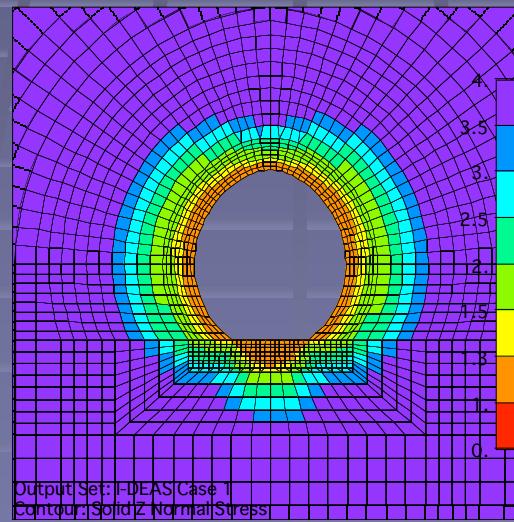
最小主応力分布 (N/mm²)

解析結果

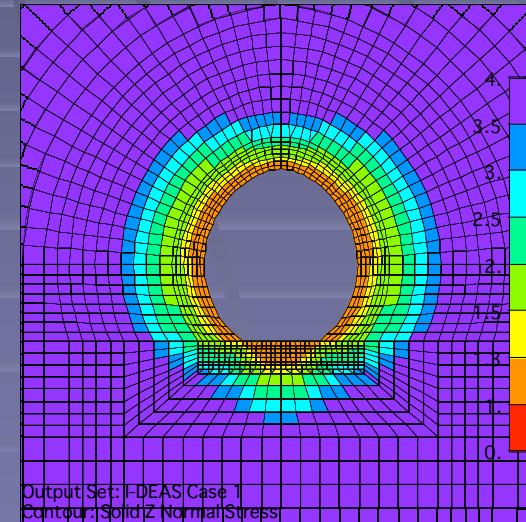
等方弾性解析



ケース 1

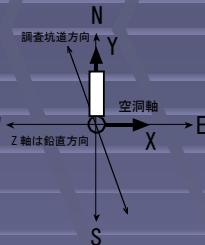


ケース 2

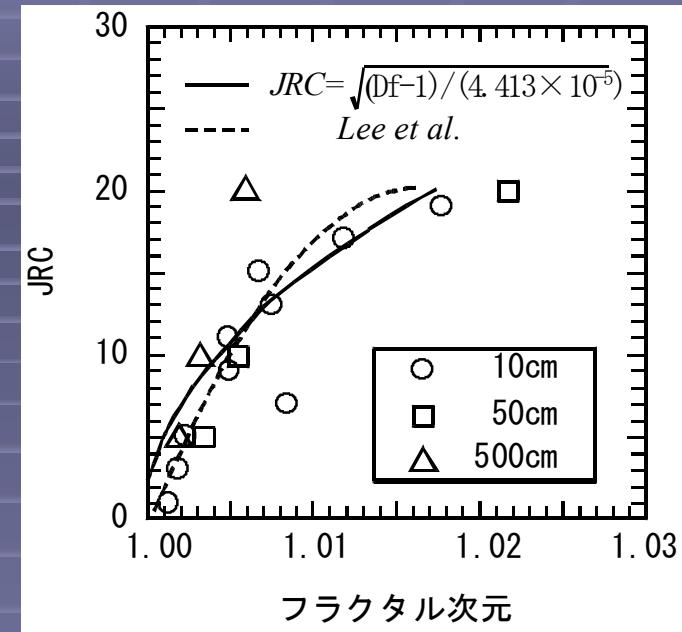
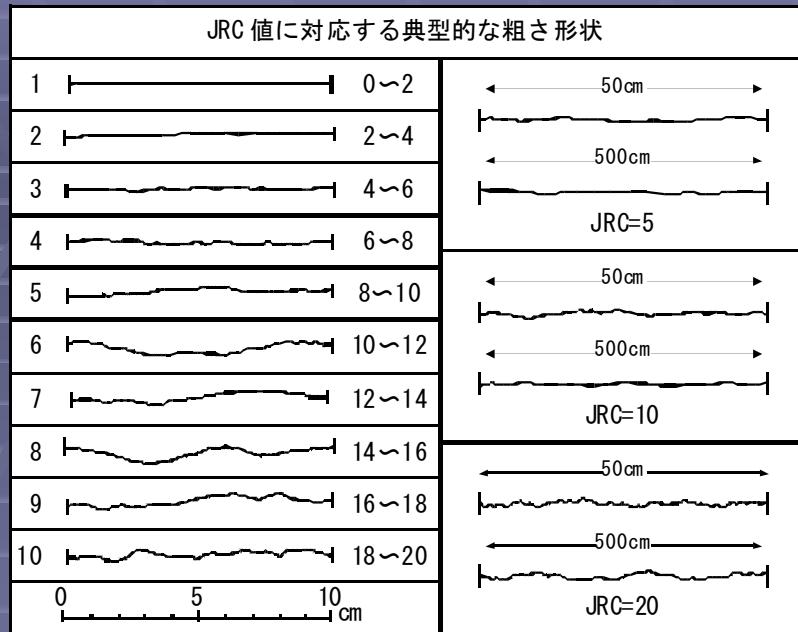


ケース 3

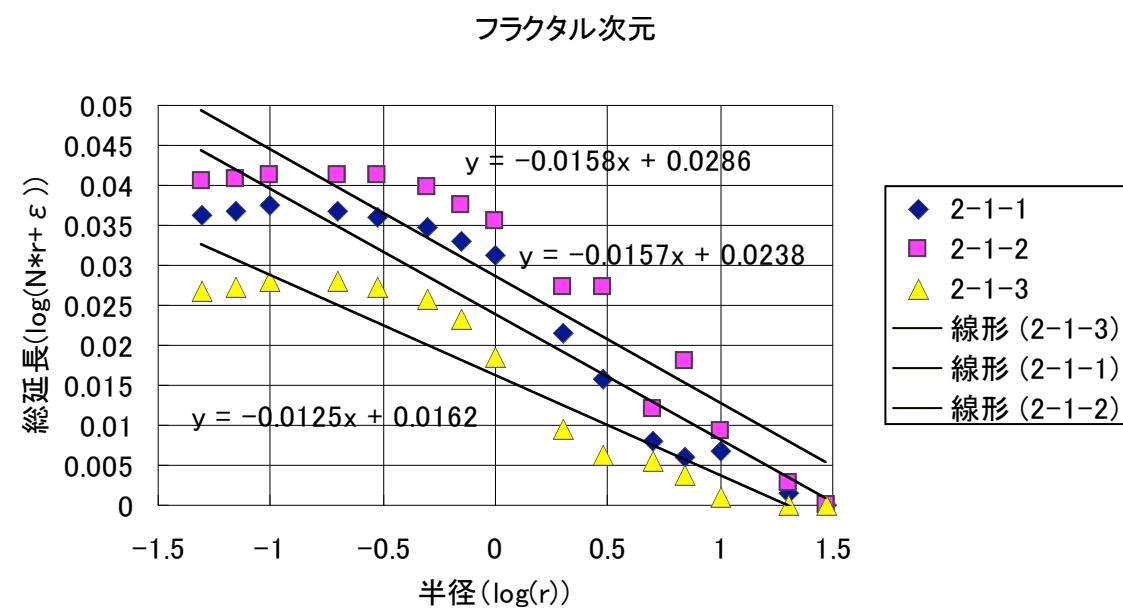
安全率分布



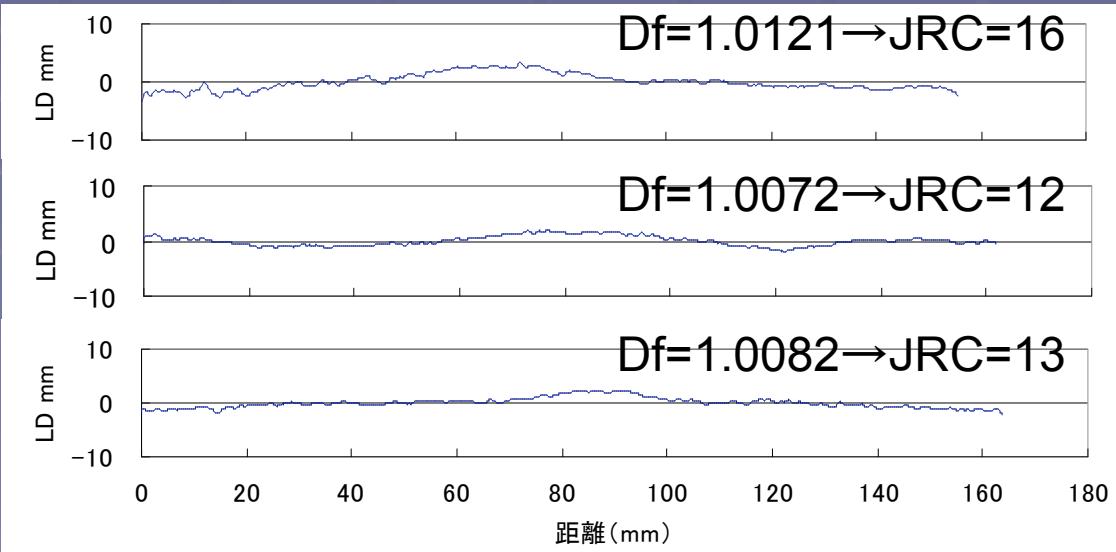
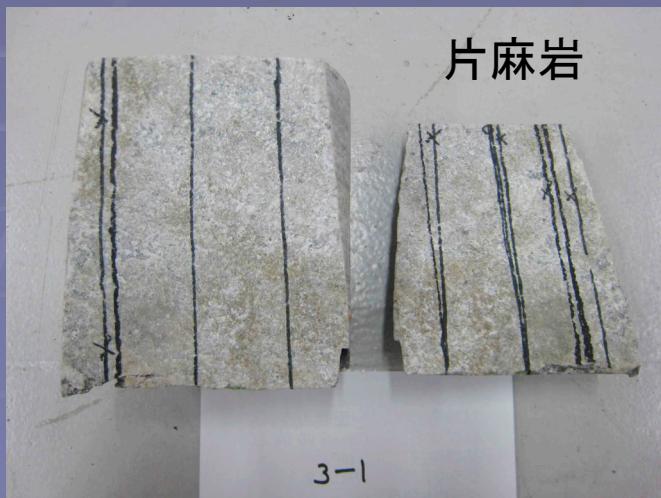
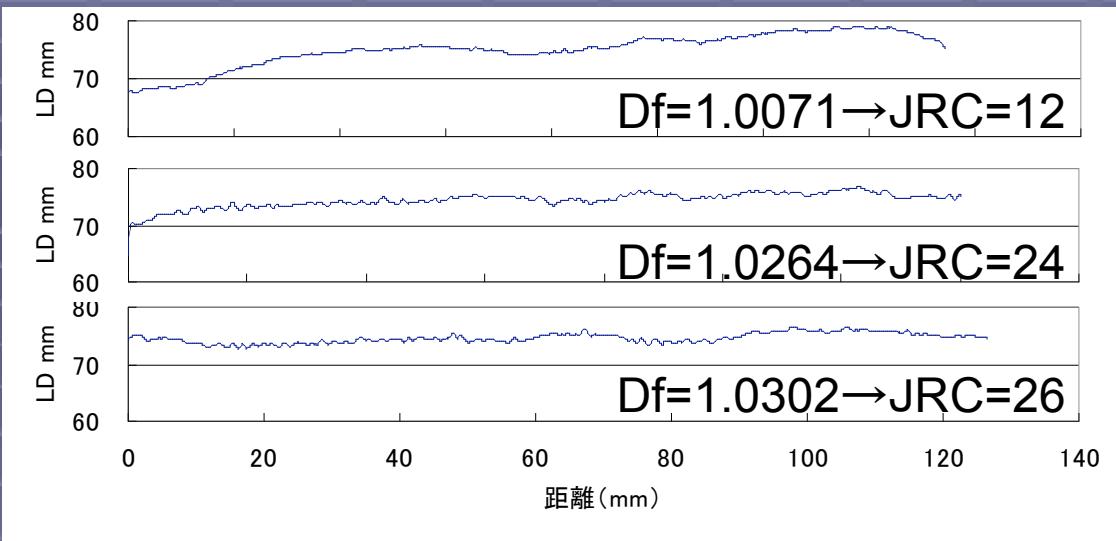
ラフネスの定量的評価



亀裂面のラフネスを測定し、フラクタル次元を算出
↓
JRCを評価



ラフネスの測定例(1)



ラフネスの測定例(2)

